

Diffractive Λ_c^+ Productions in Polarized pp Reactions and Polarized Gluon Distribution

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Abstract

To test the model of the polarized gluon distribution $\Delta G(x, Q^2)$ in the proton, we propose a new process, diffractive Λ_c^+ productions in polarized pp reactions, which will be observed in the forthcoming RHIC and also the proposed HERA- \vec{N} experiments. The spin correlation between the target proton and the Λ_c^+ produced in the target fragmentation region largely depends on $\Delta G(x, Q^2)$ and thus, the process is quite promising for testing the models of $\Delta G(x, Q^2)$.

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In these years, spin structure of nucleons has been one of the most challenging topics in nuclear and particle physics[1]. Since the surprising observation of the polarized structure function of the proton, $g_1^p(x)$, by the EMC collaboration in 1988, much progress has been attained theoretically and experimentally in the study of the spin structure of nucleons. A large amount of data on polarized structure functions of proton, neutron and deuteron were accumulated by many experimental groups such as SMC[2] at CERN and E142[3], E143[4], E154[5], E155[6] at SLAC and HERMES[7] at DESY. The progress in the data precision is also remarkable. On the other hand, the next-to-leading order QCD calculations of polarized splitting functions[8] stimulated the theoretical activities for studying the polarized parton distributions in the nucleon. Several parameterization models of polarized parton distribution functions which fit well to the data have been proposed[9, 10, 11, 12] and analyses have been developed with increasing new data[13, 14]. These experimental and theoretical developments brought about a deep understanding on the behavior of the polarized parton distribution in the proton. However, a knowledge of the polarized gluon distribution which is expected to play an important role in the so-called nucleon spin puzzle is still poor, though many processes have been proposed so far to extract information of it.

In this work, in order to extract information on the polarized gluon distribution, $\Delta G(x, Q^2)$, we propose a different process, i.e. diffractive Λ_c^+ productions in polarized pp collisions at high energies. Diffractive process which can be described by the Pomeron exchange is also an interesting current topic[15]. There have been many discussions on Pomeron interactions in these years, largely motivated by recent HERA experiments. To study this process is now quite timely because RHIC will start soon and one of the main purposes of RHIC experiments[16] is to extract the polarized gluon distribution in the nucleon from various reactions sensitive to $\Delta G(x, Q^2)$ in the proton. We expect that RHIC will also observe our proposed reactions, the diffractive Λ_c^+ production. The same process will be observed in the proposed HERA- \vec{N} experiments[17], too.

The process which we are considering here is

$$p(p_1) + \vec{p}(p_2) \longrightarrow p(p'_1) + \vec{\Lambda}_c^+(p_{\Lambda_c}) + X, \quad (1)$$

where particles with arrows indicate that they are longitudinally polarized and parameters in parentheses denote the momenta of respective particles. The lowest order Feynman diagram for this process is shown in Fig.1.

Let us start by describing why we are interested in Λ_c^+ productions. It is well-known that the Λ_c^+ is composed of a heavy quark c and antisymmetrically combined light u and d quarks,

and thus, the spin of Λ_c^+ is basically originated from the c quark. In addition, a c quark is produced from protons just through gluon fusion in the lowest order as shown in Fig.1 and hence, gluon polarization affects the spin of Λ_c^+ via c quarks produced from gluons. In other word, measurement of the spin of Λ_c^+ gives us an information on the polarized gluon in the proton[18].

The cross section of this process can be calculated based on the parton model by using the Pomeron model describing a diffractive mechanism and the model of polarized gluons, $\Delta G(x, Q^2)$, and polarized fragmentation functions, $\Delta D_{\Lambda_c^+/c}(\xi)$, of an outgoing c quark decaying into a polarized Λ_c^+ with momentum fraction ξ . One of the conventional models of Pomeron interactions is the one proposed by Donnachie and Landshoff(DL)[19], in which the Pomeron is considered to behave like a $C = +1$ isoscalar photon. Here we take this model as our first analysis. As a typical model of the polarized gluon distributions, we take GS96[9] and GRSV96[10] parameterizations among many models, since both of them reproduce well the experimental data on the polarized structure function of nucleons and thus, seem plausible. As for the polarized fragmentation function $\Delta D_{\Lambda_c^+/c}(\xi)$, unfortunately it is not known at present because of lack of experimental data, though we have some knowledge of the unpolarized function $D_{\Lambda_c^+/c}(\xi)$ [20]. However, since a c quark is heavy and hence, it is not expected to change much its spin alignment during the fragmentation process, it might not be unreasonable to use $D_{\Lambda_c^+/c}(\xi)$ for $\Delta D_{\Lambda_c^+/c}(\xi)$. Here we use the model of Peterson et al.[20] as a substitute for $\Delta D_{\Lambda_c^+/c}(\xi)$.

To calculate the cross section of this process based on the parton model, it is convenient to use the scaling variables, $x = \frac{-\Delta^2}{2p_2 \cdot \Delta}$, $y = \frac{p_2 \cdot \Delta}{p_2 \cdot p_1}$ and $z = \frac{p_2 \cdot p_{\Lambda_c}}{p_2 \cdot \Delta}$, where $\Delta = p_1 - p'_1$ is the momentum transfer of the incoming unpolarized proton. The subprocess of this scattering is

$$p(p_1) + g(k) \longrightarrow p(p'_1) + c(p_c) + \bar{c}(p_{\bar{c}}), \quad (2)$$

where g and $c(\bar{c})$ represent the gluon and c -quark(\bar{c} -quark), respectively. Momenta of individual particles are given in parentheses and are related to the ones in the physical process of eq.(1) as $k = \xi p_2$, $p_c = \frac{p_{\Lambda_c}}{\xi'}$, where ξ and ξ' are momentum fractions of the gluon to the target proton and the Λ_c^+ to the c -quark, respectively. For this subprocess, we can also define the scaling variables, $x_p = \frac{-\Delta^2}{2k \cdot \Delta} = \frac{x}{\xi}$, $y_p = \frac{k \cdot \Delta}{k \cdot p_1} = y$ and $z_p = \frac{k \cdot p_c}{k \cdot \Delta} = \frac{z}{\xi'}$. Here we follow the Schuler's way[21] to calculate the 3-body phase space for the subprocess of eq.(2). Then, we define the particle momenta in the final state $c\bar{c}$ quark(or Pomeron-gluon) C.M.S. in the subsystem (2), with $\vec{p}_c + \vec{p}_{\bar{c}} = \vec{\Delta} + \vec{k} = 0$, where the gluon momentum \vec{k} and the target proton momentum \vec{p}_2

point to the positive z direction. An angle ϕ between the proton plane ($\vec{k} \times \vec{p}_1$) and the c -quark plane ($\vec{k} \times \vec{p}_c$) is defined by $\cos \phi = \frac{(\vec{k} \times \vec{p}_1) \cdot (\vec{k} \times \vec{p}_c)}{|\vec{k} \times \vec{p}_1| |\vec{k} \times \vec{p}_c|}$. In addition to $s = (p_1 + p_2)^2$, it is convenient to define the Lorentz invariant kinematical variables, $\hat{s} = (k + \Delta)^2$, $\hat{t}_1 = (p_1 - p'_1)^2 = \Delta^2$ and $\hat{t}_2 = (k - p_c)^2$, which for $s \gg m_p^2$, can be expressed in terms of x , y , and z as $\hat{s} = (\xi - x)ys$, $\hat{t}_1 = -xys$ and $\hat{t}_2 = -\frac{\xi}{\xi'} yzs + m_c^2$, respectively.

By using these variables, we can calculate the differential cross section for the process of eq.(1) as follows;

$$\frac{d\Delta\sigma}{dydz} = \int_{x_{\min}}^{x_{\max}} dx \int_{\xi_{\min}}^1 \frac{d\xi}{\xi} \int_{\xi'_{\min}}^1 \frac{d\xi'}{\xi'} \int_0^{2\pi} d\phi \Delta G(\xi, Q^2) \frac{d\Delta\hat{\sigma}}{dx dy dz d\phi} \Delta D_{\Lambda_c^+ / c}(\xi'), \quad (3)$$

where the kinematical limits of the integral variables are given as $x_{\max} = \frac{1}{ys}$, $x_{\min} = \frac{m_p^2 y}{(1-y)s}$, $\xi_{\min} = x + \frac{4m_c^2}{ys}$ and $\xi'_{\min} = \frac{\hat{s}z}{2m_c^2} \left(1 - \sqrt{1 - \frac{4m_c^2}{\hat{s}}}\right)$; x_{\max} is determined from $-1 \leq \hat{t}_1$ which we take for ensuring the diffractive condition for the incident proton with momentum p_1 , x_{\min} from $\sin \gamma \geq 0$ where γ is the angle between the momentum of the incoming unpolarized proton and z axis, ξ_{\min} from the condition $\hat{s} \geq 4m_c^2$ and ξ'_{\min} from the requirement $-1 \leq \cos \theta \leq 1$ for the scattering angle θ of the final c -quark in the subprocess (2), respectively. In eq.(3), the polarized subprocess cross section is given as

$$\begin{aligned} \frac{d\Delta\hat{\sigma}}{dx_p dy_p dz_p d\phi} &= \frac{d\hat{\sigma}_{++}}{dx_p dy_p dz_p d\phi} - \frac{d\hat{\sigma}_{+-}}{dx_p dy_p dz_p d\phi} + \frac{d\hat{\sigma}_{--}}{dx_p dy_p dz_p d\phi} - \frac{d\hat{\sigma}_{-+}}{dx_p dy_p dz_p d\phi}, \\ &= \frac{y_p}{512\pi^4} \frac{1}{2} (|\mathcal{M}|_{++}^2 - |\mathcal{M}|_{+-}^2 + |\mathcal{M}|_{--}^2 - |\mathcal{M}|_{-+}^2), \\ &= \frac{y_p}{1024\pi^4} (\Delta|\mathcal{M}_1|^2 + \Delta|\mathcal{M}_2|^2 - 2\text{Re}\{\Delta(\mathcal{M}_1\mathcal{M}_2^*)\}), \end{aligned} \quad (4)$$

with

$$-i\mathcal{M} = -i\mathcal{M}_1 - (-i\mathcal{M}_2), \quad (5)$$

$$\Delta|\mathcal{M}_{1,2}|^2 = |\mathcal{M}_{1,2}|_{++}^2 - |\mathcal{M}_{1,2}|_{+-}^2 + |\mathcal{M}_{1,2}|_{--}^2 - |\mathcal{M}_{1,2}|_{-+}^2, \quad (6)$$

$$\Delta(\mathcal{M}_1\mathcal{M}_2^*) = (\mathcal{M}_1\mathcal{M}_2^*)_{++} - (\mathcal{M}_1\mathcal{M}_2^*)_{+-} + (\mathcal{M}_1\mathcal{M}_2^*)_{--} - (\mathcal{M}_1\mathcal{M}_2^*)_{-+}, \quad (7)$$

where $\frac{d\hat{\sigma}_{+-}}{dx_p dy_p dz_p d\phi}$ and $|\mathcal{M}|_{+-}^2$, for example, denote that the helicity of the gluon and the c quark is positive and negative, respectively. \mathcal{M}_1 is the amplitude corresponding to the subprocess shown in the Feynman diagram of Fig.1 and explicitly written by

$$\begin{aligned} \mathcal{M}_1 &= i\bar{u}(p_c)\beta\gamma^\mu \frac{i(\not{k} - \not{p}_{\bar{c}} + m_c)}{(k - p_{\bar{c}})^2 - m_c^2} (-ig_s t^a \not{\epsilon}) v(p_{\bar{c}}) \\ &\quad \times \bar{u}(p'_1) 3\beta_0 F(t) f((k - p_{\bar{c}})^2 - m_c^2) \gamma_\mu u(p_1) \left(\frac{s_1}{s_0}\right)^{\alpha(t)-1}, \end{aligned} \quad (8)$$

where β and β_0 are the charm quark-Pomeron and light quark-Pomeron couplings, respectively. $s_1 = (p'_1 + p_c)^2$ and s_0 is a scaling constant fixed as $s_0 = 1\text{GeV}^2$. \mathcal{M}_2 has similar expression which is originated from an interchange of c and \bar{c} in the final state in the subprocess. Note that \mathcal{M}_1 and \mathcal{M}_2 are added with negative sign because of positive charge conjugation of the Pomeron, as shown in eq.(5). The unpolarized cross section can be calculated similarly by replacing the polarized functions in the integrand of eq.(3), $\Delta G(\xi, Q^2)$, $\frac{d\Delta\hat{\sigma}}{dx_p dy_p dz_p d\phi}$, and $\Delta D_{\Lambda_c^+/c}(\xi')$, by the unpolarized ones, $G(\xi, Q^2)$, $\frac{d\hat{\sigma}}{dx_p dy_p dz_p d\phi}$, and $D_{\Lambda_c^+/c}(\xi')$, respectively.

The 2-spin asymmetry of Λ_c^+ is calculated by

$$A_{LL}^{\Lambda_c^+} \equiv \frac{d\hat{\sigma}_{++} - d\hat{\sigma}_{+-} + d\hat{\sigma}_{--} - d\hat{\sigma}_{-+}}{d\hat{\sigma}_{++} + d\hat{\sigma}_{+-} + d\hat{\sigma}_{--} + d\hat{\sigma}_{-+}} = \frac{d\Delta\sigma}{dydz} / \frac{d\sigma}{dydz}. \quad (9)$$

By using these formulas, we have calculated the polarized and unpolarized cross sections and the 2-spin asymmetry for the diffractive Λ_c^+ production in $p\vec{p}$ reactions at $\sqrt{s} = 50$ GeV and $\sqrt{s} = 500$ GeV, foreseeing the forthcoming RHIC experiments.

Concerning the parameters related to the Pomeron interaction, we use the same ones given in Ref.[19], such as $F(t) = \frac{4m_p^2 - 2.79t}{4m_p^2 - t} \frac{1}{(1-t/0.71)^2}$, $f(p^2 - m^2) = \frac{\mu_0^2}{\mu_0^2 - (p^2 - m^2)}$ with $\mu_0 = 1.0\text{GeV}$. The trajectory of the Pomeron is given as

$$\alpha(t) = 1.08 + 0.25t. \quad (10)$$

As for the quark-Pomeron coupling, the light quark-Pomeron coupling is fixed as $\beta_0^2 \sim 3.5\text{GeV}^{-2}$ [19]. However, it is known from experiment that the effective coupling of the Pomeron to heavy quark is rather weaker than the one of a light quark[24]. Therefore, we use $\beta \sim (m_{u,d}/m_c)\beta_0 \sim 0.23\beta_0$ for the charm quark-soft Pomeron coupling, by taking account of the mass effect of charm quark propagator in the Pomeron-charm quark vertex. Other parameters are fixed as $m_c = 1.5$ GeV and $Q^2 = (2m_c)^2$.

As mentioned above, for the polarized gluon distribution function $\Delta G(x, Q^2)$, we take two typical parameterization models of GS96[9] and GRSV96[10], while for the unpolarized distribution $G(x, Q^2)$, we take the model of GRV94[22]. For the polarized and also unpolarized fragmentation functions, $\Delta D_{\Lambda_c^+/c}(\xi')$ and $D_{\Lambda_c^+/c}(\xi')$, we use the same function of the model of Peterson et al. taken up by the Particle Data Group in Ref.[23].

Calculated cross sections and 2-spin asymmetries are presented in Figs. 2 and 3. Since the variables y and s are included in the amplitude mostly as a factorized form ys , the cross sections have almost the same behavior for the same values of ys . Since we are interested in

the target fragmentation regions, we have shown only the case with $z = 0.1$, whose kinematical range mostly covers the region with positive rapidity for the produced Λ_c^+ . Note that we have taken the z axis to be the direction of the target proton \vec{p}_2 and thus, the region with positive rapidity for the produced Λ_c^+ corresponds to the target fragmentation region. As shown in Figs.2 and 3, the 2-spin asymmetry $A_{LL}^{\Lambda_c^+}$ rather largely depends on the model of $\Delta G(x, Q^2)$ in some kinematical regions. Therefore, the 2-spin asymmetry for the proposed process is promising for testing the gluon polarization. Of course, the analysis might be rather primitive because the present calculation is limited in the lowest order. To get more reliable predictions, in addition to the next-to-leading order calculation, we have to refine the Pomeron model and also to have a good knowledge of the polarized fragmentation function of a c quark to Λ_c^+ decays. Although these subjects have their own interest and need further investigation, they are out of scope for the present work.

In summary, we have calculated the cross section and the 2-spin asymmetry for diffractive Λ_c^+ productions in polarized pp reactions for the target fragmentation region at $\sqrt{s} = 50\text{GeV}$ and 500GeV . We found that the calculated results largely depend on the model of $\Delta G(x, Q^2)$ in some kinematical regions and thus, the process is quite promising for extracting information on polarized gluons in the proton.

Although in this work calculations were carried out expecting the forthcoming RHIC experiments, the same analysis might be applied also for the proposed HERA- \vec{N} experiments.

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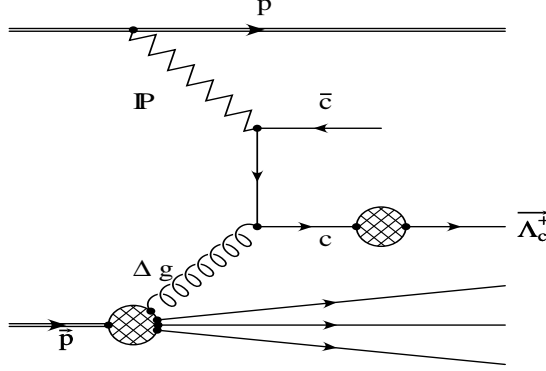


Figure 1: Lowest diagram for $p + \bar{p} \longrightarrow p + \bar{\Lambda}_c^+ + X$.

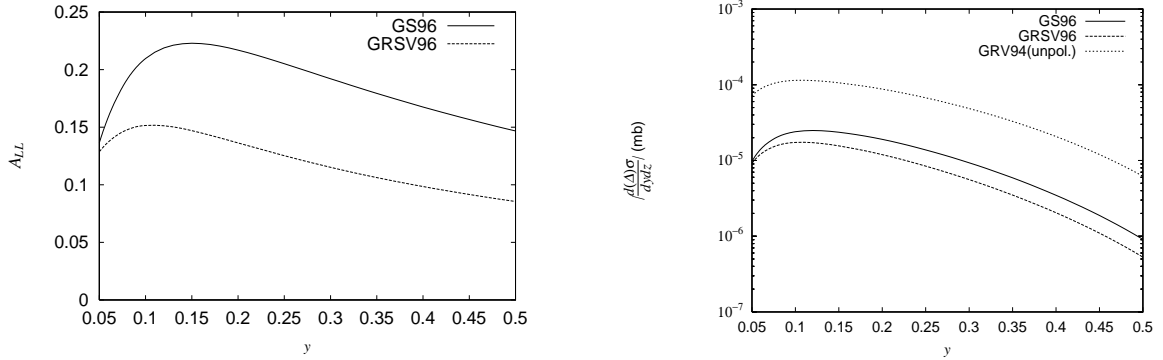


Figure 2: 2-spin asymmetry and cross sections for $\sqrt{s} = 50\text{GeV}$ and $z = 0.1$. Solid line is for GS96 and dashed for GRSV96. In the right figure, unpolarized cross section is also given in dotted line.

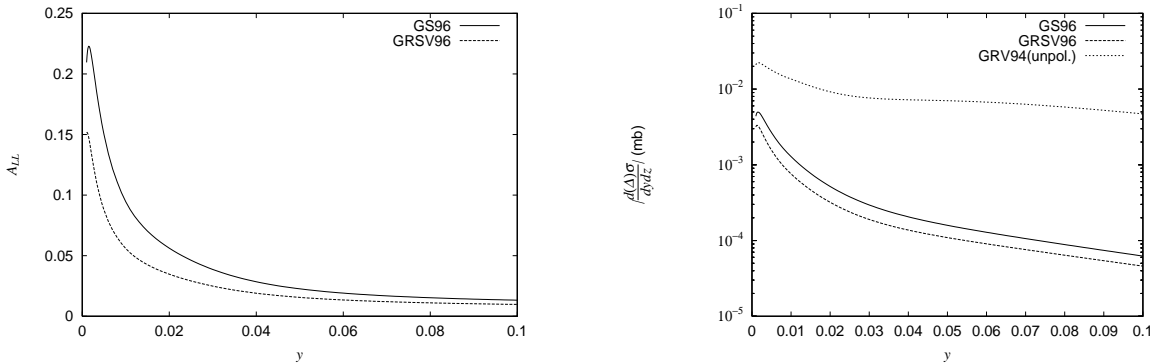


Figure 3: The same as in Fig. 2, but for $\sqrt{s} = 500\text{GeV}$.